Aqueous environments on contemporary Mars?

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ABSTRACT

If Mars evolved from a warm, wet, and biologically active planet to the cold desert conditions we observe today, then the last remnants of life would certainly have adapted to extreme tundra-like conditions. Such adaptation might take the form of an ability to thrive in occasional summer meltwater pools, or even the ability to subtly modify its environment to encourage the formation and persistence of such pools. Surprisingly, recent evidence of ubiquitous gullies and seeps at high latitudes suggest that such seasonal melting may have persisted even to the present day. Calculations presented here give additional credence to that suggestion by demonstrating that water is sufficiently metastable to form seasonally recurring meltwater pools under thin crusts of ice on present-day Mars. Moreover, the simplest of biological mechanisms, by affecting evaporative cooling rates and emissivity, could both encourage and prolong the lifetime of such pools.

Keywords: Mars, water, astrobiology

1. INTRODUCTION

Recent pictures from the Mars Global Surveyor reveal numerous gullies and channels, consistent with the flow of volatiles, that appear to be less than 1MY old.[1] This finding is surprising on a planet that is generally perceived to be dry and cold, a planet whose thin atmosphere causes rapid evaporation and sublimation of water and ice. While Mars still possesses copious amounts of water, most of it has long since frozen in the polar regions or in shallow subsurface deposits, or exists as traces of vapor and ice fog in the atmosphere. Liquid water may exist, hidden from view, kilometers underground, but it has never been observed on the surface.

Liquid water, though critical to the existence of life, is a metastable substance, constantly evaporating and freezing in any unsaturated atmosphere. Nonetheless, the persistence of a puddle or an ocean on Earth is more than sufficient to allow life to flourish. Similarly, on Mars, physics does not preclude the persistence of surface water for a few hours a day, for a few days a year, carving short gullies on hillsides, and potentially harboring life. As in cold climates on Earth, such water would typically be sheltered under a crust of ice, but that crust would be thin enough to allow the penetration of heat and sunlight. At issue is only whether the right environmental conditions exist in places where sufficient ice might accumulate to allow such seasonal melting. Prior to the observation of gullies, there had been no reason to think that liquid water might be found on such an obviously arid planet. Having re-examined that question, the obvious follow-up question is whether habitats for life might remain on Mars to this day.

1.1 Approach

Meteorological conditions on Mars have been extensively reviewed elsewhere.[2] The atmospheric pressure straddles the triple point of water, while the temperature frequently crosses the frostpoint with respect to the local humidity. As a result of these conditions, the behavior of surface water can be complex to model. The dominance of evaporative cooling over convective exchange with the atmosphere is in striking contrast to terrestrial experience. As a result, water can be stable in what appear to be inhospitable conditions. Moreover, because atmospheric convection and ground conduction are extraordinarily low compared to Earth, extremely large thermal gradients may exist as a result of local topography.

Mars Global Surveyor images have revealed numerous gully features at high latitudes and altitudes, typically on pole-facing slopes.[1] Since these are locations likely to harbor near-surface or condensate ice late into the summer, the most straightforward explanation of the gullies is seasonal melting of condensed volatiles (water, CO_2, or some combination of the two). Moreover, since the features are only hundreds of meters in length, water would only need to flow for hours at a time to carve them.

Mars' cold, arid climate results from the fact that it receives only half the solar energy as the Earth and lacks Earth's greenhouse effect. However, it has long been established[3,4] that liquid water, if present on Mars, would flow over extensive distances and persist for long periods of time. Compared to comparably cold places on Earth, water on Mars would lose heat more rapidly from evaporative and radiative cooling, less rapidly from convective cooling. As will be shown, the net difference is small. But while convection is sensitive primarily to wind and temperature, evaporative and radiative cooling reflect local conditions such as emissivity, geometry, and salinity.

At the lower elevations found in much of the northern hemisphere of Mars, the present-day atmospheric pressure varies between 7 and 10 mbar. This pressure range is slightly, but distinctly, above the thermodynamic triple point of water, 6.1 mbar (4.6 Torr). Viking Lander 1, at 22°N latitude, measured 6.8-9.0 mbar, while Viking Lander 2, at 48°N latitude, measured 7.5-10 mbar. Mars Pathfinder measured the lowest values, 6.7-7.1 mbar. This low pressure results in a low boiling point, less than 10°C, but has little impact on the energetics of the liquid phase. Even on Earth, the energy required for either the liquid-solid phase transition (334 J/g) or the liquid-gas transition (2500 J/g) is prodigious compared to the amount required to raise the temperature from the freezing to the melting point, 1 J/g-K.[5]

At other locations, at high altitudes and in southern latitudes, the total atmospheric pressure frequently falls below the vapor pressure of the liquid. Under these circumstances directly exposed water is, technically, unstable, and rapid evaporation would cause a thin crust of ice, millimeters to centimeters thick, to form at the surface. The surface temperature of this ice would be a few degrees below the freezing point, reducing the vapor pressure above the surface and suppressing the rapid evaporation. As can readily be observed in cold terrestrial climates, a modest layer of surface ice has little effect on the general character of hydrological features. Thus, by itself, even instability with respect to evaporation does not preclude flowing or pooling water on the surface of Mars.

This paper reviews plausible local conditions on Mars, either naturally occurring or biologically induced, that would allow ice to melt and water to flow. Despite the low atmospheric pressure, water at 0°C on Mars will evaporate no faster than 60°C water on Earth. Freezing rates on Mars are limited by the rate that heat can be removed from an icy surface,[3,6] perhaps a few millimeters per hour (~1 kW/m^2 is required to melt 1 cm/hr). Neither evaporation nor freezing rates provide an insurmountable obstacle to the steady flow of liquid.

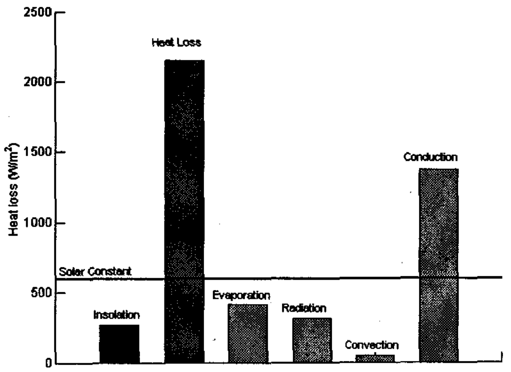
1.2 Conditions at thermal equilibrium

Ice will melt on Mars when the heat input from the sun at the melting temperature exceeds the sum of the heat loss processes from the ice. On Earth, convective losses to the atmosphere typically determine the thermal equilibrium between water and atmosphere. In the thin air of Mars, however, convective losses are small. Radiative losses to Mars' cold sky are somewhat greater than on Earth, and evaporative heat loss is large. Conductive losses below the water are substantial if the bed consists of ice, more modest for a bed of highly-insulating Martian soil.[7]

The rate at which water evaporates on Mars, compared to the total inventory of water, is small. This is because, for ice at the freezing point, the heat of vaporization is approximately 7.5 times the heat of melting. As a result, in absence of heat transfer to or from the environment, 7.5 grams of water will freeze for every gram that evaporates. Evaporation is, however, a primary engine of freezing. A rapidly-evaporating pool of water, lacking a heat source, will freeze without substantial loss of mass.

In the most favorable conditions for melting, direct insolation is the dominant source of heat. Counterbalancing solar heat input are predominantly convective cooling to the atmosphere (assumed to be at a nominal temperature of 200K), evaporative cooling, radiative cooling to an extremely cold sky, and conductive cooling to the ground.

Histograms in Figures 1 show widely different scenarios for the thermal equilibrium of a pool of water, at the freezing point, under nominal Martian conditions. The scenario on the left might be typical of published models.[3,6,8-10] It assumes conduction through a thick bed of ice (equilibrated for one hour), and radiation from a high emissivity, flat surface. Evaporation is calculated for open water under a 10 mbar atmosphere with little wind, but results would be similar for ice-encrusted water at lower pressures. The surface albedo is assumed to be 0.25 (actual values range from less than 0.1 to greater than 0.35), and the optical depth 0.1 (representing a clear sky). The sun angle is assumed to be 45° to the surface normal, an average value appropriate for phenomena requiring heat input over many hours while the sun moves across the sky.



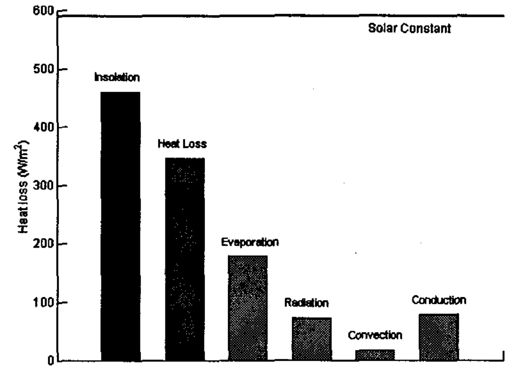


FIGURE 1.Left: Heat loss from water or ice at 273K on Mars, compared to solar constant. The bar labelled "heat loss" is the sum of evaporative, radiative, convective, and conductive losses. Under these typical conditions, ice would not melt. See Table I for parameters and assumptions. Right: Best case heat balance, indicating in excess of 100 W/m^2 available for melting (corresponding to melt rate of 1 mm/hr)

Table I: Physical parameters assumed for Figs. 1 and 2.

Parameter	Fig. 1	Fig. 2
Solar Constant (W/m^2)	589	589
Albedo	0.25	0.1
Optical depth	0.1	0.1
Latitude	70°	70°
Sun position in sky	45°	45°
Solar angle to local surface	45°	0°
Wind speed (m/s)	10	<2
Atmospheric pressure (mbar)	10	10
Atmospheric temperature (K)	200	200
Surface temperature (K)	273	267.4
Emissivity	1.0	1.0
Apparent emissivity	1.0	0.25*
Sky temperature (K)	100	100
Temperature of base (K)	200	223
Conductivity of base (W/cm-K)	.022 (ice)	.00077
Heat capacity of base (J/g-K)	2.01 (ice)	0.59
Density of base (g/cm^3)	0.9 (ice)	1.5
Equilibration time (hour)	1	2

**At edge of a depression with depth(D)=width(W), or center of a depression with D=2W.*

For ice to melt, the total heat loss from the pool of water must be less than the heat input. For the conditions assumed on the left, evaporative losses, radiative losses, or conductive losses can each independently overwhelm the direct heat input from the sun. Ice will not melt under these conditions. Despite the cold atmosphere, however, it is noteworthy that convective cooling is negligible. This is because of the low heat capacity, and hence the low heat transfer coefficient, of the rarified gas comprising the Martian atmosphere. It follows that atmospheric temperature is a largely irrelevant measure of the "coldness" of Mars in this context.

The thermal balance on the right in Figure 1 represents more optimal meteorological and geometrical circumstances. It represents the time of day when incident sunlight is normal to local slopes, although the sun is allowed to be quite close to the horizon. Moreover, the albedo is assumed to be 0.1, at the more extreme end of the measured distribution but consistent with high latitudes and the dark-colored gullies observed in the images.[1] Further, the calculation assumes a local geometry that provides partial "shade" from the cold sky (i.e. low apparent emissivity). Importantly, it assumes a thin sheet of ice overlying soil (equilibrated for 2 hours), or soil mixed with ice, because a thick ice sheet is too thermally conductive to allow sufficient thermal gradients at the surface. It also assumes a surface temperature of –5°C. This lowering relative to the melting temperature may be due to the presence of 4-5 cm ice on the water, 2-3 moles/liter of dissolved salts in the melt water, supercooling, or some combination of the three. With these new assumptions, the balance sheet in Fig. 2 indicates a net gain in heat, resulting in a substantial rate of melting.

2. THE INFLUENCE OF BIOLOGY ON MELTING AND FREEZING

Detailed derivation of the heat transfer formalism has been presented elsewhere,[11] but the arguments can readily be reconstructed from standard texts. This section will focus on a description of favorable environments for melting, and on ways in which biology could further modify those conditions to enhance the likelihood and persistence of meltwater.

2.1 Insolation

The total absorbed radiation from the sun is a function of the position of the sun in the sky, the relative slope of the surface, the optical depth, and the albedo of the surface. The maximum height of the sun above the horizon at any latitude L higher than the planetary inclination (I=25°) is $I_{max}=90°-(L-I)$. On Mars, the albedo ranges from 0.1-0.35, with low values characteristic of subpolar latitudes where gullies are prevalent.[12] Moreover, the gullies typically appear dark, indicating a low albedo. The optical depth typically varies from 0.1-1.0, with lower values common at higher altitudes.

Figure 2 displays the maximum insolation vs. latitude for a sun-facing slope at the peak of a clear day in midsummer. The lower curve shows the insolation vs. sun angle to normal. While latitude has an enormous effect on *average* insolation, it can be seen that the *peak* illumination is not particularly sensitive to latitude. Surprisingly high peak temperatures may be obtained even at extremely high latitudes.

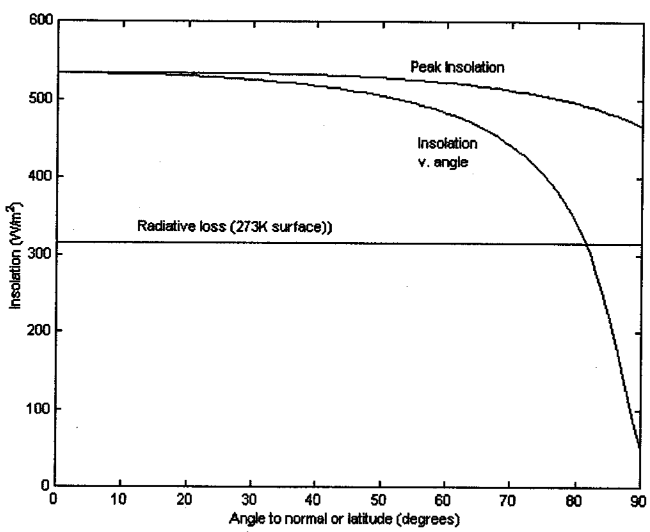


Figure 2: Maximum insolation for a sun-facing slope, assuming an optical depth of 0.1, zero albedo, and a scale height of 11 km, (representing a clear day and ignoring the possible additional contribution of scattered light). The middle curve shows the effect of off-normal angles of illumination. Typical radiative loss from the surface of water/ice is shown for comparison.

Because an open pool of water would never be sun-facing at high latitude, it would tend to lose more heat from the surface than would be gathered from sunlight. However, the ubiquitous presence of an ice crust over meltwater in this environment makes it possible for water to pool under a more optimal, sloped ice surface.

Control of albedo is an obvious means for biology to impact heat retention. Most biological materials have an unusually low albedo compared to mineral surfaces. This evolutionary adaptation not only captures the optimal heat for individual organisms, but arguably has modified the Earth's climate on a global scale. Terrestrial sandy loam, for example, has an albedo of 0.24, comparable to that of much of Mars. Moist, organism-rich soil, by comparison, has a typical albedo of 0.08.[13] In fact, before the Mariner probes revealed the surface of Mars to be apparently lifeless, seasonal darkening observed from terrestrial observatories was widely interpreted as a sign of vegetation.

On a larger scale, strong feedback mechanisms would encourage colonies of microbes in high latitude zones to create corrugated structures that would capture normal-incidence sunlight for at least part of the day, for part of the year. This strategy sacrifices average heat for peak heating, a mode well suited to organisms that can lie dormant between occasional periods of active metabolism and growth.

2.2 Radiation

The radiative loss to the cold Martian sky is $I_{rad} = \varepsilon a(T^4 - T_{sky}^4)$, where ε is the emissivity (typically at least 0.95 on Mars) and the Stefan-Boltzmann constant $a=5.7\times10^{-8}$ W/m^2-K^4. The Martian sky temperature, T_{sky}= 62-113K as measured by Pathfinder, is so much colder than the surface of melting ice that it can be approximated as 0K. Earth's sky, by comparison, is often as warm as 260K, barely colder than the melting point of ice. As a result, radiative losses to the sky are at least six times greater on Mars than on Earth. Nonetheless, when the sun is at normal incidence to a local surface and when the sky is clear, the radiative equilibrium temperature may still equal or exceed 273K anywhere on the planet.

Geometry, however, can sharply reduce radiative losses from melting ice. In shallow basins, gullies, or below scarps, radiation from melting surfaces to the sky may be replaced by the lesser radiation to nearby sun-warmed surfaces. In essence, these geometries provide "shade" from the cold sky. This factor is captured in the radiation equation by replacing ε with an apparent emissivity, ε_{app}, reflecting the fraction of the 2π solid angle actually exposed to the sky.

Lacking constant sunlight, such sheltered locations will usually be cold. When exposed to the sun, however, they can be extraordinarily warm. This has been noted by Kossacki *et al*,[14,15] who suggest unusually high peak temperatures inside a robotically-excavated trench. In practice, there is an optimal aspect ratio that encourages melting or sublimation. Too deep, and the sun will shine on the bottom too infrequently. Too shallow, and the radiative losses to the sky prohibit effective heating.

Using this fractional solid angle to determine the apparent emissivity, Fig. 3 maps the thermal losses across the bottom of a hole for depth-to-diameter ratios between 0 (flat surface) and 4. Dramatic reduction in radiative losses can be seen for even the shallowest basin, particularly at the edges. The apparent emissivity, ε_{app} can readily be a factor of two or more smaller than the overall emissivity, ε. This effect can be dramatically observed in recent MGS photos of frost in craters (right). The absence of frost near the walls corresponds to regions suffering the least radiative cooling. It is important to note that there is no scale factor dictating this geometric effect. It operates as readily on millimeter-scale biological structures as on kilometer-scale craters.

The only common materials with emissivity dramatically below 0.9 are polished metal surfaces. While not impossible, it is unlikely that biological structures could retain heat by direct control of emissivity. More plausible might be the utilization of macroscopic geometric structures for this purpose. Organisms could opportunistically utilize natural structures. They could encourage the development of such structures by a dappled growth pattern that would promote nonuniform erosion (particularly in icy areas). Moreover, simple evolutionary mechanisms could readily encourage the development of high-aspect-ratio structures, thereby accelerating growth in the warm, sheltered areas of a microbial mat.

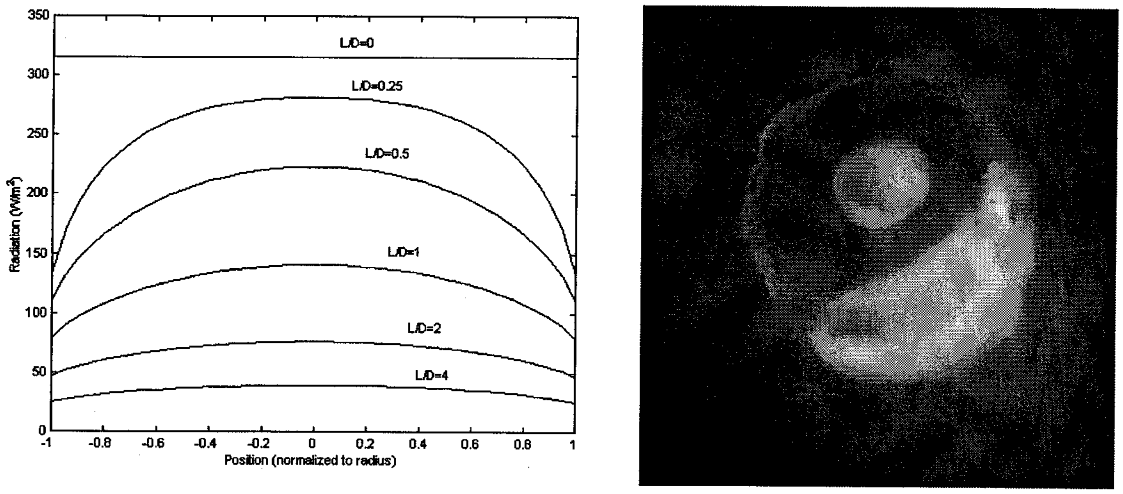


FIGURE 3: Left: Relative radiative loss to sky across the floor of a basin, for various depth (L) to diameter (D) ratios. L/D=0 corresponds to a flat surface. An isothermal temperature of 273K is assumed. Right: MOC2-258b, Northern Spring, 71°N, 257°W, Unnamed Crater, October 6, 2000, 48 km (30 mi) across. Frost persists in the most exposed, central region. (Image Credit: NASA/JPL/Malin Space Science Systems)

2.3 Evaporative and Convective Cooling

Evaporation and convective cooling are discussed together because they are essentially the same phenomenon – the movement of low-density warm or humid air away from a surface under the influence of gravitational or shear (wind) forces. Evaporative cooling dominates on Mars, while convective cooling dominates on Earth, but the net heat loss is similar for comparable atmospheric temperatures. This is particularly noteworthy in that convective cooling is difficult for an organism to control, while evaporation can more readily be mitigated. In this sense, a cold environment on Mars poses less of a thermal challenge to an organism than a comparably cold region on Earth.

The total rate of gas evolution from the surface of liquid water or ice can be accurately determined from the known vapor pressure.[16] But the actual rate at which evaporation occurs is limited by the diffusion of this vapor from a humid boundary layer into the dry atmosphere. The contributions of geometry, atmospheric dynamics, and turbulence, make such a calculation approximate at best. Derivation of evaporation and convection rates can be found in many texts on heat transfer.[17,18] In general, the rate of heat transfer per unit area from a warm wall to cold atmosphere can be written in terms of a temperature difference and a heat transfer coefficient h,

$$\frac{q}{A} = h(T_{wall} - T_{\infty}) = Nu\left(k\Delta T / x\right) \quad (1)$$

where Nu is the dimensionless Nusselt number, k is the conductivity, and x is a characteristic dimension.Under calm conditions, free convection will prevail, in which case the Nusselt number can be determined from the Grashof and Prandtl numbers. For a horizontal surface under relevant conditions,

$$Nu_f = 0.15\left(\mathrm{Gr}_f \mathrm{Pr}_f\right)^{1/3} = hx/k \quad (2)$$

where the subscript f indicates that the quantities are evaluated at the film temperature, $T_f=(T_{inf}+T_{wall})/2$. The Prandtl number, $Pr=c_p\mu/k$ has a value near unity. It is relatively insensitive to pressure, and is not significantly different on Earth and on Mars. Here, μ is the dynamic viscosity (evaluated at ∞) and c_p the heat capacity. The characteristic dimension x will cancel in this special case of a horizontal surface.The Grashof number may be written as

$$Gr = \frac{\rho^2 g\beta\Delta T x^3}{\mu^2} \tag{3}$$

where, β, the volume coefficient of expansion, is $\Delta\rho/\rho$ for mass convection, $\Delta T/T$ for thermal convection; ρ is the total density of saturated gas at the evaporating surface; g is gravitational acceleration; V is a volume element; and T is the gas temperature.

Equations analogous to thermal convection describe the rate of mass transfer m' in terms of a difference in concentration ΔC (mass/volume solute) and a mass transfer coefficient h_D:

$$\frac{m'}{A} = h_d\left(C_{surf} - C_\infty\right) \tag{4}$$

The principal physical difference between thermal and evaporative transport is the fact that one depends on thermal diffusivity, $\alpha = k/\rho c_p$, while the other depends on mechanical diffusivity, D. The dimensionless ratio of the two is termed the Lewis number, $Le=\alpha/D$, whose value is typically close to unity. Since the two transfer coefficients are closely related, consistency demands that they be calculated using the same model. The ratio of the heat transfer coefficients can be written in terms of the Lewis number as

$$\frac{h}{h_d} = \rho c_p Le^{2/3} \tag{5}$$

where ρ is the mass density and c_p the heat capacity. Thus, in this formalism, the evaporative mass loss is

$$E = h_d\Delta C = (0.15)\frac{D\Delta C}{x}\left(Gr_f \Pr_f Le\right)^{1/3} \tag{6}$$

where D is the diffusion coefficient and $\Delta C \sim\rho_w$ is the difference in vapor concentration (mass/volume solute) between the surface and the surrounding atmosphere, where ρ_w is the density of water vapor at the source temperature and vapor pressure

For comparison, the evaporation formula of Ingersoll[19] can be written as $E = (0.17)\frac{D\Delta C}{x}Gr^{1/3}$.

Figure 4 (left) compares both forms for Earth and Mars gravity and gas composition. Curiously, it can be seen that the net effect of buoyancy of water vapor (reflecting molecular weight and viscosity of the air as well as the gravitational constant) is nearly identical on the two planets. To apply these formulae to Mars, consider a body of pure liquid water, possibly ice-encrusted, at 273K under a cold, 200K atmosphere. Neglecting the coupling between the two processes, the ratio of convective cooling to evaporative cooling can be shown to be proportional to the atmospheric density, ρ.[18] This comparison is illustrated in Fig. 4 (right), which indicates that the total heat loss due to the two mechanisms is actually *less*, for equivalent temperatures, on Mars than on Earth. Minimal heat loss would occur when the two loss mechanisms were comparable, at approximately 80 mbar. Because the atmosphere of Mars is so thin, convective cooling is equivalent to that produced by only a few degrees of temperature difference (ΔT) on Earth. By contrast, the evaporative cooling of this water on Mars is substantially greater than on Earth.

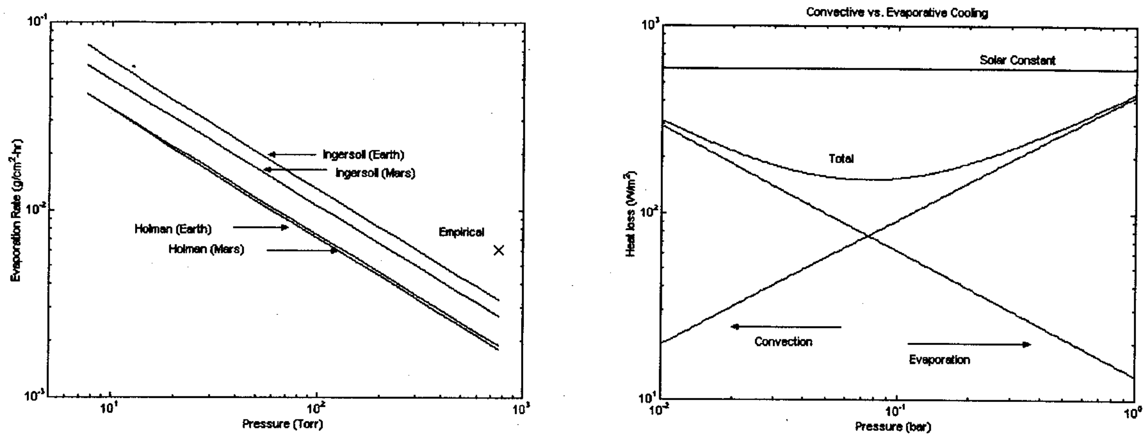


Figure 4: Left: Using either the model of Ingersoll[19] ("Ingersoll") or Eq. 6 ("Holman"), predicted evaporation rates as a function of pressure on Mars (in CO_2) and on Earth (in air or N_2) are nearly identical. All calculations are for 0°C. An empirical value for terrestrial evaporation is shown for comparison.. Right: Convective heat transfer between a 273K surface (water) and a 200K atmosphere compared to evaporative cooling. The right hand boundary reflects terrestrial conditions, the left martian. For equivalent atmospheric temperatures, total heat loss is actually less on Mars than on Earth.

For still air, this model will indicate the most severe evaporative losses, those corresponding to a surface water/ice temperature of 273K. Since the evaporation rate is proportional to the vapor pressure at the surface, it can be suppressed by lowering the equilibrium surface temperature. This may result from an insulating ice barrier between the ice/water interface and the water/air interface. For example, assuming the thermal conductivity of the ice is 0.022 W/cm-K, a 5°C temperature drop and 300W/m^2 heat flow correspond to 3.67 centimeters of ice. Low surface temperature may also result from a reduction in melting point due to salinity in the water or supercooling. For example, since the cryoscopic constant for water is K_f=1.86 K-kg/mol at 0°C, 3 moles/liter of a solute lowers the melting point to -5.58°C. From Raoult's law the vapor pressure at any given temperature is also lowered by an amount proportional to the mole fraction of solute. For this example, Raoult's law causes an additional 5.1% reduction in vapor pressure, resulting in a vapor pressure of 3.8 mbar, well below the 6.1 mbar characteristic of pure water. The corresponding reduction in evaporative cooling is proportional to the reduction in vapor pressure. High salinity would not be surprising in local pools of meltwater, since solubles leached from entrained dust would tend to concentrate during the freezing process.

By breaking down insoluble components of dust and rock, biological systems could increase the ion content and reduce the equilibrium temperature of their host pool, thereby increasing heat retention. A simpler mechanism, more peculiar to biological systems, is also relevant. It has long been known that monolayer-thick layers of certain polar molecules can reduce the evaporation rate of water by more than 50%. Cetyl alcohol, for example, has been extensively used in agriculture to reduce evaporation from reservoirs, and in the cosmetics industry to enhance the effectiveness of moisturizing droplets. In reservoirs, the principal drawback of this technique has been the disruption of the surface layer by wind – a condition likely to be far less severe on Mars. Even a small colony of microbes could produce a sufficient quantity of such a substance to dramatically increase heat retention of their local environment.

2.4 Conduction

Conductive heat loss to the ground beneath a pool of water or stream imposes the most severe constraint on the production of meltwater on Mars. Martian soil, being pathologically dry, is a superb insulator. Ice, by comparison, is highly conducting. Thus the areas most conducive to melting are those in which thin ice overlays dry soil.

The conductive loss to soil will vary with time as a stream-bed warms up and the loss of heat into the ground is slowly reduced. As we are considering melting at the peak of the day, the relevant heat loss is the one that results from 1-2 hours of heating. This loss rate can be determined from the one-dimensional solution to the time-dependent heat loss equation,

$$q(t) = k(T_{surf} - T_{soil}) / \sqrt{\pi \alpha t}\ , \tag{7}$$

where $\alpha = k/\rho c_p$, ρ is the soil density, k the conductivity , and c_p the heat capacity.

Ice is relatively conducting, with k=0.022 W/cm-K, c_p=2.01 J/g-K, and ρ=0.9 g/cm^3. Soil, however, may be highly insulating, with some authors[7] suggesting values as low as k=.00077 W/cm-K, c_p=0.59 J/g-K, and ρ=1.5 g/cm^3. The difference between these two extremes can be dramatically seen in Fig. 1.

The necessity to heat up the ground beneath the ice introduces a lag-time after the location is exposed to full sunlight and prior to melting. Sheltered locations that limit radiative loss to the sky must be sufficiently exposed that they can receive sunlight for a few hours a day. The bed must remain insulating and impermeable even when occasionally covered with liquid water. This requirement eliminates, for example, the utility of snow as a promising site for melting. The ambient temperature of the ground also enters into the conductive heat loss equation, practically the only parameter that favors a low-latitude site.

As a result of these considerations, the most likely sites for melting are probably layered, with an insulating, impermeable bed underlying a thin ice layer. Dry soil is sufficient with respect to conductivity (0.77 mW/cm-K), while compact snow is marginal (2.1 mW/cm-K) and ice is definitely too conducting (up to 22 mW/cm-K). Since neither snow nor soil is impermeable to water, a frozen layer would have to overlay the base if a significant amount of water is to accumulate. Biology, however, provides another alternative. A wide variety of biological materials have superb insulating properties, from beeswax (0.38 mW/cm-K) to diatomaceous earth (0.45 mW/cm-K). No doubt these insulating properties have evolved on Earth for precisely the reason they might evolve on Mars – to provide protection against a cold environment. On Mars, a bed of impermeable, insulating biological detritis could encourage the seasonal appearance of meltwater.

3. DISCUSSION

Surrounded as we are by water, it is easy to overlook the fact that the liquid phase is not, technically speaking, stable on Earth. Life on Earth is possible because liquid water is sufficiently metastable that evaporation and freezing occur on a scale of hours or days, a slow effect compared to the macroscopic motion of water. If liquid water were introduced on Mars, the same metastability would be seen. Mars is dry primarily because it is cold, not because of a fundamental instability of water.

It is not claimed here that gullies on Mars were necessarily formed by contemporary melt-water, only that physics does not preclude such an origin. The conditions for ice accumulation and melting provide a framework for testing this melt-water hypothesis. If geometric, radiative, and thermal properties of gullies can be shown to correspond to those described here, and if sufficient seasonal accumulation of ice can be demonstrated, then it is likely that meltwater is the correct explain. Most of this information can probably be gathered by remote sensing.

Ice accumulation is a slow process, particularly in insulated locations favorable to melting, because the ice layer must continuously shed the substantial heat of condensation. Melting, by contrast, is most efficient when it occurs suddenly and rapidly. Locations that are extremely cold for most of the year, and anomalously warm in the peak of the summer, are therefore the most likely places on Mars to find melt-water. It is telling that gullies are observed predominantly in just such locations. Pole-facing slopes at higher latitudes will be cold for much of the year, anomalously warm when the sun shines on them in midsummer. The dry surfaces will present an insulating substrate to a thin layer of surface ice. Alcoves and gullies provide shelter against excessive radiative cooling to the cold sky in summer, when the adjacent dry surfaces are warmed by the summer sun, but will cool to absorb the radiated heat of condensation in perpetual winter shadow. On Earth, similar late-season runoff has been observed from accumulation of winter ice in alcoves in arctic terrain.[20]

On Mars, water is predominantly metastable with respect to freezing, not evaporating. This is due not so much to the low average temperatures, but to the low atmospheric pressure. While the sparse air insulates surfaces against convective cooling, it enhances evaporative cooling. The net cooling rate for water is similar to that found in a cold climate on Earth except that, on Mars, evaporation (rather than convection) is the engine of freezing via latent heat loss. Both evaporation and freezing are slow processes. Evaporation of water at 0°C on Mars proceeds at a rate comparable to evaporation at 60°C on Earth, while freezing proceeds at comparable rates on both planets if temperatures are similar.

For liquid water to flow on contemporary Mars, two things must occur. First, sufficient ice or snow must accumulate to provide a source for the melt-water. Second, before the ice sublimates, the temperature must rise to the melting point and heat input must exceed heat loss. A thin surface layer of ice may be part of that requirement if the atmospheric pressure is too low to accommodate the vapor pressure of the liquid.

While a favorable heat balance might seem unlikely on such a cold planet, poor atmospheric convection and low soil conductivity allow for local warm patches nearly anywhere on Mars. Under the favorable circumstances described here (shallow basins, sun-facing slopes, clear skies, reduced surface temperature, and ice overlying soil), the thermal balance in Fig. 1 indicates that in excess of 100 W/m^2 net heat input may available to melt ice.

3.1 Distribution of potential meltwater sites

Consider three zones of potential meltwater formation: dry equatorial and temperate latitudes, the polar ice caps, and the subpolar regions of seasonal frost and midnight sun.

The low and middle latitudes are the least likely places on Mars to find meltwater. If ice were present it might readily melt, since the ground is relatively warm in summer, and nearly any local slope can experience overhead sunlight for a portion of the day. For precisely these reasons, however, this is the least likely place to find ice. Any frost that accumulates at night is quickly driven off by morning sun. Near-surface ground water, over the aeons, has frozen, sublimated, and migrated to the poles, with no known hydrological transport systems to replenish them. Residual outcroppings of ice and permafrost, if they existed, would likely be too conducting to allow melting. Ironically, because of its ready accessibility to spacecraft, this region is the most extensively studied by landers.

The polar caps are only slightly more likely to harbor water. Particularly in the north, the poles are clearly rich in water ice. Intricate texturing has been widely observed, so geometrically favorable configurations are no doubt present. Indeed, these structures were likely carved by precisely the thermal mechanisms described in previous sections. The ice itself, however, poses a severe barrier to meltwater formation. While published models differ as to the consistency of the surface ice, none of the models seem favorable to melting. If the surface is porous firn ice, it might be sufficiently insulating to allow melting, but any such melt water would rapidly disperse in the porous medium. If the surface consists of compacted slab ice, it would be too conducting to allow the local surface heat concentration necessary for melting. The only promising circumstance would be the accumulation of thin ice over an insulating layer of packed dust. Layered terrain, readily visible around the circumference of the pole, suggests that the pole experiences alternating periods of accumulation and ablation, most likely corresponding to periodic variations in orbital parameters. During periods of ablation, embedded dust becomes concentrated at the surface, creating the distinct dark streaks. If such a layer of compacted dust were both thermally insulating and impermeable, subsequent accumulations of ice might melt in the summer, forming lenses of water between a surface ice crust and the underlying soil.

Between the temperature latitudes and the poles lies a region that experiences seasonal frost accumulation and long, dark winters, yet shows a bare surface in the summers. In this zone, particularly at high altitudes, all the requirements for melting could conceivably be satisfied. Moreover, locations favorable to melting would likely produce meltwater on a periodic, annual basis. The ground is likely thermally insulating, and frost can accumulate over many months of darkness or shadow. During the summer, the low sun provides normal-incidence illumination to nearly any pole-facing hillside, and local topography offers shelter from wind, and shade from the cold sky. The most likely form for melt-water would be a trickle from alcoves, down a hillside. Once pooled at the bottom, the re-frozen water would be unlikely to melt again, since its horizontal surface would not experience normal-incidence sunlight. It is by no means evident that sufficient ice could accumulate from frost alone to allow for summer melting, but other mechanisms are possible. For example, as water vapor sublimates from more exposed areas in springtime, it could redeposit in these more sheltered locations.

3.2 The case for life

It is not argued here that life could, should, or does exist on contemporary Mars. But assuming that life once existed on a warm, wet Mars, how would it have evolved as the planet became cold and dry? Arguably the last viable habitats (and the only ones that could clearly exist today) would have been seasonal pools of liquid water. Organisms with the ability to survive long seasons of extreme conditions, only to flourish in a short growing season, are hardly rare on Earth. Any organisms surviving in a hostile Martian climate would have had similar characteristics. Obvious adaptations that would prolong the active season would have been evolutionarily favored. One such adaptation, for example, might be a low albedo surface.

In this context, it is important to note a large advantage enjoyed by hypothetical Martian organisms over their terrestrial cold-weather counterparts. On Earth, systems of organisms lose heat primarily by convection to the air. The only way to defend against convective heat loss is with massively thick layers of insulation. Moreover, the thickness of the insulating layer does not scale well, if at all, with the size of the organism. On Mars, the analogous biological systems lose heat not by convection, but by conduction, radiation, and evaporation. As has been shown in this paper, nature offers barriers to conduction, and biology can offer protection against both radiation and evaporation. Furthermore, such protection *does* scale with the size of the organism. Small corrugated surfaces work as well as large corrugations to reduce radiative losses. Small dark surfaces work as well as large dark surfaces to enhance solar absorption. And only minute amounts of organic substances are needed to dramatically reduce evaporative losses from a pool of water.

For organisms to have survived the end of a putative fertile period on Mars, more than the presence of water would have been necessary. Nutrients, for example, would be required, as would a means of exchange of material between isolated, possibly transient oases. Dispersed sites harboring life would have required periodic replenishment of water. As with other considerations in this paper, physics does not preclude the existence of such mechanisms even today. The subpolar locations considered for melt-water formation would, indeed, be periodic. Mars has an active system of particle transport that, in the presence of water, can take the form of ice fog. Furthermore, elemental analysis of martian dust allows the possibility that it is rich in salts of evaporitic or volcanic origin, suggesting a mechanism for replenishment of nutrients in seasonal water.

In summary, if life still exists on Mars, it likely survives by perturbing its environment to conserve liquid water. If so, its signature would consist of occurrences of contemporary water flow exceeding the statistical likelihood. Future study will determine if we have found such evidence already.

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